Future Mars Outpost Architecture[1]

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Abstract—NASA's Mars Exploration Program includes science goals related to life, climate, geology, and preparation for human exploration. Many of the investigations needed to reach these goals are enabled by long-term, continuous surface presence with logistical support. These capabilities can be provided by a progressive series of missions that establish and maintain a long-lived robotic presence, i.e. a Mars Outpost.

To investigate the issues associated with robotic outpost design, the JPL Mars Long Range Planning Team developed and studied a heuristic outpost scenario. Major goals of the study included identifying: (1) which science objectives benefit from an outpost setting, (2) technology needs to fulfill mission requirements, and (3) operational/logistical challenges associated with multi-mission planning. This paper describes an outpost designed with the aforementioned goals in mind. The design focuses on subsurface mapping and characterization, accomplished through seismic mapping and deep drilling.

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1. INTRODUCTION

Outpost Definition and Rationale

Definition—One way to portray the evolution of space exploration is as a sequence of overlapping eras, each era succeeded by another embodying more challenges and more mature objectives. One model suggests that we are currently in the third era (consisting of occasional visits for short periods of time with focused objectives), and that the focus of the fourth era will be the evolution from occasional visits to permanent bases supporting the continuous presence of robots and/or humans. Another term applied to such bases is "outposts," used in the traditional terrestrial sense to suggest a continuous presence, e.g. a base of operations, beyond the edge of settled civilization. The new twist about applying the traditional outpost notion to space exploration is that the presence may be robotic—initially or permanently—rather than human. Such an extra-terrestrial outpost would be constructed, maintained and expanded through a series of linked "missions," landing new payloads at the selected site.

Mars Outpost Examples—While the outpost concept is very appealing and potentially applicable in many places throughout the solar system, it seems particularly easy to visualize robotic outposts on Mars, in places such as:

- The poles – To look carefully for water, evidence of life, evidence of climate changes, and to watch the seasons change.
- Olympus Mons – To continuously monitor and study the solar system's largest volcano and search for evidence of recent volcanic activity.
- The Great Valley, Valles Marineris – To search for water and seek to understand the tectonic origins of this huge rift valley.

Rationale for Mars Outposts—Mars ranks high in all the attributes that invite the long-term, continuous presence of robots. For example:

- Compelling scientific challenges are plentiful, consistent with NASA's basic goals.
- Long-term, continuous data sets are needed.
- Outposts can serve as stepping stones to elsewhere – either elsewhere on Mars or elsewhere in the solar system.
- Utilizable resources to boost self-sustainability are present.

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- There is a need to prepare for human presence, because of the high probability that human-enabled science is required to fully understand the location.
- There is a need for application of scientific techniques requiring continuous, relatively high, power levels (e.g., deep drilling) or application of techniques not amenable to long sample transit times (e.g., "wet" chemical or biochemical analysis), or execution of experiments of relatively long duration that are too dynamic to be completely pre-planned from Earth.
- Existence of the water and life mysteries, climatological dynamics, dramatic terrain, as well as a level of general knowledge and interest, make Mars an engaging place for long-term exploration.

Finally, long term continuous presence will give people here on Earth the opportunity to truly participate in the exploration process.

Outpost Formulation and Design

Formulating and designing outposts and outpost programs has many facets that are either absent or of less importance in formulating and designing "current era" missions.

Siting—Determining the outpost site takes on much greater importance because of the major, long-term commitment to the site. In the case of Mars, there are currently many potential attractive outpost sites. Given current knowledge (or lack thereof) regarding the best place to find compelling evidence of life, water, or geologically revealing terrain, it is difficult to pick the best site for an outpost. Such factors being equal, secondary operational factors may be extremely important (e.g. ease of communicating with Earth, and/or attaining the necessary Mars orbit). Selection of specific Martian site(s) probably should await increases in knowledge to be provided by current and near-term Mars missions—especially orbiters such as MGS, Mars Odyssey 2001, ESA's Mars Express Mission, and the 2005 Mars Reconnaissance Orbiter. Site selection for a first Mars outpost could take place with much greater confidence (at least with respect to water and geological potential) as early as 2007 if these planned missions complete their objectives successfully.

Design Process—The design process is more complex for outposts than for single missions, since sets of closely linked missions must be designed more or less simultaneously, according to an overall outpost utilization strategy. Trades between mission cost, launch vehicle cost, outpost functionality and risk, operations cost, and so on, must be done among an element set instead of for a single landed element. Moreover, technology evolution must be projected as accurately as possible, and factored into the design process. Missions later in the outpost sequence should be able to capitalize on cheaper, more rugged, longer-lived, higher performance technologies as they emerge.

Evolution—The evolution of an outpost is a critical concern. An overall strategy (e.g., set of utilization goals, "backbone" systems design, operating philosophy) is needed for the use of the outpost. However, the key to maximizing its utility is applying resources to new tasks—new explorations, new experiments, new instrument deployments, etc.—in response to results and findings not originally anticipated.

Logistics—Finally, all this requires application of the art and science of logistics, something unfamiliar to current day robotic mission designers.

While these factors will be critical to outposts of any kind, anywhere on Mars, there are so many different opportunities on the Red Planet that if we are to deepen our understanding we must look at specific scenarios. How much science can be accomplished at an outpost? What are the key "backbone" systems or assets needed? What are the key enabling technologies? What is the right way to think about evolution and logistics? The remainder of this paper describes an attempt to develop a specific robotic Mars outpost scenario in sufficient detail to provide one set of specific answers to these questions.

2. FINDINGS: SCIENCE BENEFITS OF OUTPOST

Approach

The conceptual outpost scenario described here was developed as a heuristic exercise, to answer the aforementioned questions. At the outset of the task, initial working assumptions and drivers were identified which led to a preliminary equipment roster and operational scheme. The feasibility of this baseline scenario was investigated, by tapping into the knowledge base at JPL as well as seeking expertise from other NASA centers, outside agencies, institutes and private industry. The gathered information led to refinements of the assumptions and outpost architecture, until this final version was reached. The scenario itself represents half of the product of the study, with the balance consisting of findings, i.e. the science, technology and logistical lessons learned along the way.

Working Assumptions and Drivers

Outpost Focus—Many outpost sites and objectives, including those in the examples given in the introduction, could have served as suitable starting points for a study of this type. But because it seemed to provide a clear but challenging objective, ground-based subsurface mapping and characterization were selected as the main focus of the outpost. This was the primary driver of the initial outpost design. To avoid limiting the flexibility of the scenario, an exact site was not specified. Instead, as will be explained in later sections, provisions for site selection were incorporated into the scenario itself.

The sub-surface mapping objective led to the inclusion of a seismic data collection scheme in the outpost design. A deep drilling scheme with core-sample retrieval capability was also added to the scenario. This was intended to provide the necessary calibration information for the seismic data as well as a greater level of detail for the subsurface characterization. However, the main driver for the inclusion of the deep drill was the simple desire to investigate the feasibility of an operation as complex as autonomous deep drilling, from a logistical viewpoint.

Operational Assumptions—The requirement for long-term operation and interdependent missions creates several constraints on the outpost equipment and the operational scheme.

Long-lived equipment is clearly necessary, but achieving a long life span involves trade-offs between complexity for performance and robustness for durability, as well as between expensive, repairable units and relatively cheap, replaceable ones. This issue was noted, but only roughly addressed during the course of this study.

This conceptual outpost is a single string design, with no "built-in" spares integrated into the launch manifest. It includes provisions for replacing simple components only, including rover batteries, drill stems and power tethers. However, the ability to replace elements after equipment breakdowns or launch/landing failures remains a key aspect of the outpost, because of its overall multi-mission approach, wherein the launch order can be manipulated and/or additional payloads can be selected and launched as needed. Part of the study included determining which elements were the critical reliability drivers, and thus where redundancy could be most effectively implemented.

The basic interdependency of outpost elements implies the ability to land subsequent payloads sufficiently close to a centralized location, or the ability to transport landed payloads from their landing site to the outpost location. For this study, it was assumed that mature precision landing techniques were available.

Past robotic missions to Mars have required teams of operators to carry out operations on the surface. As the outpost evolves, it would become increasingly labor-intensive to retain a team of operators for each individual element. Thus it was also assumed that autonomy would be incorporated into the outpost equipment, wherever possible. This would come to include such things as automatic hazard avoidance and navigation for mobile elements, autonomous sensor deployment, autonomous fault detection, etc.

Element Assumptions—Assumptions were made for each individual piece of equipment that was integrated into the outpost design. Those will be explained in the Operational Description section, which details each outpost mission, its payload and operational scheme. However, there are a few element assumptions that affect the scenario as a whole.

Historically, the life of any space mission is limited by the life of the power source. For this outpost design, a space nuclear reactor was selected as the main power source. This was done in order to eliminate life limitations imposed upon the more traditional photo-voltaic systems due to dust accumulation, and to allow continuous power production irrespective of changes in season or dust storms. Also, at higher power levels (above a few kilowatts-electric) reactors provide a low specific mass power system option. The general need for low specific mass, high-power systems for large-scale space exploration in the future also contributed to the desire to study the feasibility of using a nuclear reactor on the surface of Mars.

For launches, both Lockheed Martin and Boeing's Evolved Expendable Launch Vehicles (EELV) were assumed to have become fully operational before the first outpost launch. Launches were planned using the Delta II, Delta IV Medium, Delta IV Heavy, and Atlas V Medium launchers.

The payloads were designed for a worst case launch opportunity (using a C_3 of 18), which allows the initial launch year (and thus each subsequent launch) to be changed without affecting the launch order or payloads. In general, individual element mass estimates were generated by extrapolating from previous designs, where they were available (for example, the rovers were assumed to be more massive than previous Mars rovers or concepts, due to added redundancies for longer life, and the addition of large batteries). Where such similar elements were not available, rough estimates were made based on the advice of technologists both within JPL and in industry.

A further assumption was the inclusion of HDTV cameras on each rover and at least one additional location at the outpost site, and the continuous broadcasting of HDTV data. This would establish a true "virtual presence" at the outpost, and provide a valuable avenue for public engagement. This had a direct impact on the design of the scenario, as it increased the complexity of the communication infrastructure required to handle the data stream.

From these assumptions and the information gathered from the consulted sources, a conceptual design for a robotic Mars outpost was developed. Equipment development and launch vehicle costs were estimated and a rough cost profile was developed, though those figures are not included here. This multi-faceted, multi-mission scheme is not part of the current Mars program plan, nor is it tailored to fit within the current NASA budget. The following section gives the details of the scenario.

Elements by Launch Opportunity - Overview

This outpost scenario consists of a series of linked missions beginning in 2009, with at least one launch every opportunity through 2022. The scheme also includes a contingency plan that will be enacted upon the discovery of significant quantities of liquid or solid water.

Table 1 lists essential equipment and brief operational objectives, by launch opportunity. Further details on the individual elements, operational scheme and proposed launch vehicles are given in the following section.

Table 1: Outpost Equipment Roster by Launch Opportunity

Baseline Scenario		
Launch Opportunity	**Primary Payload(s)**	**Operational Objective(s)**
2009	Long Range Rover	Locate initial outpost site
	Navigation Beacon	Provide location signal for future landings
	HDTV Camera	Establish virtual presence
2011	Mars Towing Rover	Transport seismic lab and the drill, replace batteries for all rovers (using a robotic arm)
	Mobile Seismic Lab	Begin high-resolution subsurface mapping
	Communication Hub	Expand communication capability, support climate sensors to obtain continuous, long-term data sets
2014	Space Nuclear Reactor	Power the drill and other equipment
	Deep Drill	Calibrate seismic data and produce core samples
	In-situ sample analysis equipment	Analyze core samples from drill
	Logistics Supplies	Provide additional drill stems and tether
	Comm. Satellite	Expand communication capability
2016	Science Rover	Enhance mobile science capability
	In-Situ Science Instruments	Enhance science capability
	Logistics Supplies	Provide additional drill stems and tether
2018	Sample Return Orbiter	Provide Earth Return Vehicle for samples
	Mars Ascent Vehicle	Transfer samples from the surface to the orbiter
2020	Human Precursor Demos	Prepare for human exploration
	ISRU Equipment	Demo In-Situ Resource Utilization
2022	Advanced Robotic or Human Operations Gear	Enhance robotic capability and/or prepare for human arrival
	Advanced Mobile Units	Expand current outpost and/or traverse to new site

H_2O Contingency Scenario		
Launch Order	**Primary Payload(s)**	**Mission Objectives**
1	Wet Chemical Analysis Instruments	Add capability for analysis of liquid samples
2	Wet Sample Return Orbiter and Ascent Vehicle	Add capability for return of liquid and/or frozen samples
3	ISRU Systems	Add capability for utilizing H_2O resource

Operational Description

The following sections describe the individual outpost elements in greater detail. The assumptions and operational scheme associated with each piece of equipment is explained, including how they interact to accomplish the goals of the outpost.

Opportunity 2009: Reconnaissance—An initial zone of interest can be identified using data from existing orbital platforms and past landed missions. However, as previously discussed, the long-term commitment to the outpost site increases the importance of the initial siting. Therefore, to ensure that the best location is chosen, the outpost scenario begins with the launch and landing of a long-lived, long-range rover for ground reconnaissance within the selected zone.

The site selection involves parameters such as level of scientific interest, compatibility with the operational objectives of the outpost (in this case, primarily the seismic and drilling schemes) and relative scarcity of landing and mobility hazards. Once a site is selected, the rover sets a navigation beacon in place, to provide a homing signal for the following missions. The reconnaissance rover carries a small scientific payload as well, and conducts limited science observations/experiments. Once its power supply becomes insufficient to continue these operations, it switches into a low power "sleep" mode to await the arrival of the next outpost flight.

Long-Lived, Long-Range Rover—To complete its task of site selection as well as subsequent science investigation and exploration, the long-lived, long-range reconnaissance rover must be robust, with the capability to traverse rough terrain. To achieve a long life span, it is designed to be re-energizable. Initially, it would be powered with a set of primary (non-rechargeable) batteries. These are replaced with a new set using the robotic arm on the towing rover, after the arrival of the second outpost flight (see below). Later still, the second set of primary batteries will be replaced by rechargeable ones. This allows the rover to take advantage of power supplied by the space nuclear reactor, which would be launched in the third opportunity. Since it does not rely on solar power, this rover concept can function during the night and in dusty conditions, using radar for navigation and hazard avoidance.

A prototypical long-lived long-range rover has been studied [1]. That concept uses advanced solar power technology and travels roughly 2 km per sol. It has a design life of two years (with a goal life of four years) and a lifetime travel range of about 1000 km. The rover for this robotic outpost is loosely based upon this concept. Primary and later rechargeable batteries were incorporated rather than solar arrays, to provide a renewable power source. This concept is expected to have a similar rate of travel, and have the ability to rove for periods on the order of one month between charges. The use of replaceable batteries, along with other design modifications such as critical system redundancies, is intended to increase the overall life span of the rover. The outpost long-range rover might have a mass from 200 to 300 kg, and be launched on a Delta II class launch vehicle. A conceptual drawing of the vehicle is shown in Figure 1.

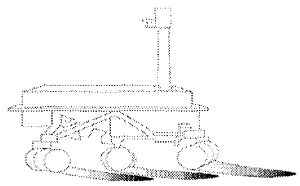

Figure 1: Long-lived, Long-Range Rover

HDTV Camera—The rover also carries a High-Definition Television (HDTV) camera, to transmit high-quality video footage to Earth (as does each subsequent rover, the deep drill and the communication hub). This is the first step towards continuous HDTV coverage of outpost activities, in order to establish a "virtual presence". The cameras are modeled after current commercial cameras available through Sony. They each use 40 W of power, have a mass of 8 kg and a resolution of 1920x1080 pixels. These commercial cameras can operate between 0 to 40 degrees C and can be stored between –20 to 60 degrees C. Because of the expected temperatures during cruise and on the surface of Mars, each camera uses thermal devices to maintain its temperature within these ranges. The camera on this initial rover begins to transmit video once the outpost communication hub arrives.

Opportunity 2011: Seismic Survey—In the second opportunity, a mobile seismic lab, towing rover and communication hub are sent to the outpost site. Their arrival begins a phase of intensive seismic mapping of the region. The data are transmitted to Earth, where they are used to determine the best location to land and set up the deep drill. After the initiation of the drilling campaign, the survey can be expanded into other regions of interest, or the sensors can be left in one location to monitor any natural seismic activity.

Mobile Seismic Lab—The purpose of the Mobile Seismic Lab (MSL) is to conduct active seismic sounding within an area on the order of 20 square kilometers, using both reflection and refraction techniques to map near-surface stratigraphy. The soundings can also confirm the presence of a liquid/ice water layer, to a depth of 3-4 kilometers, with an uncertainty on the order of 10 percent. The design of the MSL was driven by a number of factors, including resolution, independence, and mobility.

Initially, an active acoustic thumper was considered to provide the necessary vibration. However, this approach was determined to be mass and power prohibitive. A Delta IV Heavy launch vehicle could be used to transport a massive thumper to the surface and the reactor could be sent in this opportunity to provide adequate power to operate it. However, this scheme would require deploying and moving many kilometers of power tether, as well as the massive thumper, multiple times during the seismic survey. To avoid these complications, the design was changed to include small explosive charges (used for most terrestrial surveys). Similar explosives are commonly flown on space vehicles for such purposes as flight termination and payload separation. The reduction in power requirements resulting from this change allows the seismic lab to be battery powered and this initially independent from the nuclear reactor, so that element can be sent on a later launch. The MSL was also initially envisioned as a separate powered rover. However, as the scenario evolved and the Mars Towing Rover (as described in the following section) was introduced, it became more practical to use it to provide transportation and sensor deployment for the seismic lab rather than continue to carry separate roving capability.

The final concept for the MSL is a wheeled cart housing 25 seismic sensors and 100 1-kg explosive charges. It would be towed from site to site, where the rover distributes 20 sensors in two perpendicular, linear arrays forming a large L, and places a detonation charge at the intersection (five sensors are included with the main package for redundancy). Each leg of the array is a kilometer long, with the sensors placed 100m apart. The rover moves the MSL cart a safe distance away and the charge is detonated, producing a radially propagating seismic wave. After detonation, the arrays are pivoted 180 degrees and another charge set for detonation. After the second such charge, the arrays are moved to the next location and the process is repeated.

Seismic Sensors—Both sensor arrays have a main sensor that acts as the transceiver for that array. Every sensor in the array has a small transmitter to send its data to the main sensor. In turn, the main sensor relays all of the data to the communication hub to be sent back to earth directly (or in later years, via the communications orbiter). Each sensor would be an ultra-broad-band (UBB) seismometer with high-volume telemetry, measuring solid body tides, normal modes, surface waves, and high-frequency body waves. The data return is about 500kbits per probe per charge, with a resolution on the order of 10 meters. Using lithium-ion batteries, they could have a life-span of two to five years (their low mass of about 8 kg allows for easy replacement on later flights, if the survey is continued). Figure 2 shows a conceptual drawing of the MSL, including a dish for data relay to the communication hub and the seismic sensors.

Figure 2: Mobile Seismic Lab

The seismic data would be analyzed on Earth to determine specific points of interest for drilling or possible sample acquisition. Autonomous drilling devices, or moles, could be included in the scenario, which can be deployed (one at a time, as needed) by the towing rover to provide calibration for the seismic data as well as more detailed investigation of multiple interesting sites.

Mars Towing Rover—The primary function of the towing rover would be to provide transportation for outpost elements. It is designed as a tracked vehicle, to provide the traction and torque necessary for towing as much as 3000 kg of equipment. It uses a robotic arm and hooks attached fore and aft to mate to wheeled loads. A communication antenna mounted on a retractable boom allows the rover to establish a line-of-site link to the communication hub over long distances. This boom also allows elevation of a HDTV camera and radar sensors to allow the rover to see over obstructions. Such radar sensors allow the rover to safely travel in zero-visibility dust storms. Such booms have been successfully demonstrated on numerous space missions. With the boom retracted, the entire rover assembly measures less than 1m high and will easily fit into an aeroshell for EDL operations. As with the reconnaissance rover, it would be powered by primary batteries until the arrival of replacement rechargeable batteries in the third set of outpost flights. The robotic arm would be used to replace rover batteries as well as deploy seismic equipment and explosives. The towing rover has multiple batteries and must have redundant electronics as well, to allow it to use the arm to replace its own batteries when necessary. Figure 3 provides an illustration of this rover concept, showing a dish for data relay to the communication hub, the robotic arm, treads, and a cutaway to reveal the batteries.

Towing Tasks—The greatest load for the rover would be the deep drill system, which is estimated to weigh 1500 kg. The drill would be precision landed at the first drill site, but may be towed for repositioning in case of initial drill casing/drill bit failure, or to allow additional drill sites to be explored. Drill rods, packaged in dispenser units containing 250 meters of drill rod apiece, are transported to the drilling site by the rover as well. The rover would later responsible for laying out power tethers from the nuclear reactor to the drill and rover recharging-stations (total of about 20 km, or 2000 kg). If necessary, it repositions other outpost elements, including the communication hub, human precursor and technology demonstration equipment. These towing rover tasks are intermittent (for example, the drill system would be stationary for up to three years, during it's deep drilling campaign). Thus, the towing rover would also be used to move and deploy the seismic lab, eliminating the need for an additional rover dedicated to that task.

The robotic arm would be sized to allow lifting of a 50-kg battery. The rover travels relatively slowly when towing a heavy load, for instance on the order of 100m per sol when moving the drill or laying tether. It would need to return to recharge regularly when towing such a load over great distances. With battery replacement, the towing rover has a goal lifetime on the order of fifteen years. It might weigh on the order of 800 to 1000 kg, and be launched, along with extra batteries, on a Delta IV Heavy vehicle.

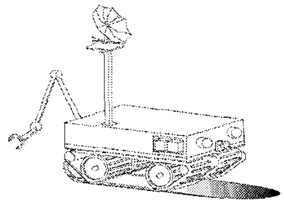

Figure 3: Mars Towing Rover

Communication Hub—The communications hub will improve the communication link between the outpost and the Earth. The hub would be launched in 2011, and acts as the main communication relay for the outpost until the communication satellite arrives. The main driver of the outpost communications infrastructure is the HDTV live data stream, which is estimated to be 20 Mbps using current MPEG-2 compression. A 5-meter High Gain Antenna (HGA) mounted on the hub handles this high data rate transmission. It can be mechanically deployed or inflated.

The HGA would be a 100-watt Traveling Wave Tube Antenna (TWTA), using either Ka- or X-band frequencies to communicate to the Deep Space Network (DSN). In the timeframe of this outpost scenario, it is assumed the DSN dishes will be able to accommodate the 20-Mbps data rate.

Two atmospheric masts that house various sensors are also mounted on the hub. These vertical masts extend about one meter up and one meter towards the ground. They support evenly spaced temperature and pressure sensors, with wind sensors on the extremities. These low-power, low-mass sensors would collect long-term, continuous data sets, recording the climate of the outpost site. An additional navigation beacon would be attached to the hub as well, as a redundant twin to the first beacon that was emplaced by the long-range rover.

In terms of power, the hub must be self-sufficient until the arrival of the nuclear reactor with the next mission. It requires a total of 140 W of power (this includes a 35% reserve) for two years. Multijunction GaInP/GaAs solar arrays were examined as a possible power source for the hub during this period. These have an efficiency of 25.7%, currently the best laboratory value achieved [2]. Total surface area required is estimated to be about 8 m^2, assuming a maximum deflection of 60 degrees from perpendicular to the sun. The area could also be separated into 3 or 4 smaller arrays and gimbaled to remain perpendicular to the sun during most of the day. The area estimation also accounted for a 0.03% loss per day for dust (assumes that an unspecified type of active dust mitigation is used) over the two years. Assuming 25 W/kg, the mass for the arrays (not including batteries for nighttime operation) would be 15.2 kg.

As with the long-range rover, primary batteries could also be used to power the hub until the arrival of the reactor. Once the nuclear reactor reaches Mars, a tether would be attached to the hub to provide all future power. Figure 4 depicts the communication hub, with the solar array option.

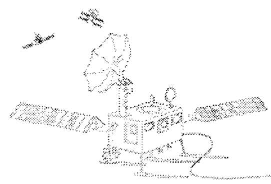

Figure 4: Communication Hub

Opportunity 2014: Drilling Campaign—The third launch opportunity would necessarily be heavily booked. The nuclear space reactor would be sent at this time to provide a power source for the ensuing operations. The drill lands to begin its subsurface exploration tasks, at the site selected through the seismic survey. In-situ sample analysis equipment would analyze the core samples retrieved by the drill. Power tether and drill stems are included in the payload of the flight with the analysis equipment. Finally, the communication satellite would be sent to enhance the communication infrastructure of the outpost.

Space Nuclear Reactor—Power for the outpost would be provided by a nuclear reactor, based upon a concept developed at NASA Glenn and inputs provided by Department of Energy (DOE) [3]. The outpost reactor would be fueled with uranium enriched in the isotope U-235, and is designed to remain subcritical until activation is desired. Activation would be achieved by rotating moveable reflectors into place. These are turned to reflect a sufficient number of neutrons back into the core in order to achieve a controlled and sustained chain reaction. These reflectors provide a means for deactivating as well as throttling the reactor. Additionally, internal safety rods that absorb neutrons are placed within the core and must be withdrawn before the system can be activated.

This concept includes limited radiation shadow shields to protect electronics. The shielding creates a protected cone, or "shadow," extending from the reactor. It is assumed that advanced precision landing techniques will reduce the landing error of this flight to the order of 1 km. This removes the necessity of moving or repositioning the reactor with the towing rover. Thus, the shielding should be designed so that it, rather than the whole reactor, can be repositioned by the towing rover. Outside of this protected area, there exists a zone in which operations with electronics may need to be limited if left unshielded. This would depend on both the distance from the reactor and the time of operation in this zone. Precision landing capabilities should allow repeated landings within the reactor shadow, once it is established. This is especially important for stationary equipment such as stationary science equipment, the deep drill, and the communications hub. The use of in-situ shielding (i.e., indigenous materials or terrain features) may also be feasible but was not investigated.

The reactor would be launched, transported to Mars and landed in a "cold" state with reflectors turned away and safety rods in place. The fuel would be essentially non-radioactive prior to reactor startup. Before its activation, the towing rover would lay out three 1-km tethers in a fan pattern from the reactor, inside the protected shadow. Two of them would act as rover charging points, from which any of the outpost rovers could draw power to recharge their batteries. The third would act as the connection point for additional tether to the deep drill.

With the minimal shielding, 3 Brayton cycles and cooling radiators, the 20 kWe reactor weighs about 1800 kg and has a life expectancy of about five to seven years. It would be launched on a Delta IV Heavy. Figure 5 illustrates the conceptual reactor design, showing three deployed radiators for cooling, and power tethers extending to one side. The shielding is not shown.

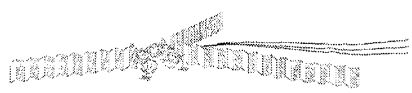

Figure 5: Nuclear Reactor

Deep Drill—The Mars outpost drilling system must be versatile, autonomous, durable, and mobile. The primary drill task would be to verify subsurface formations, determine material constituents, and retrieve core samples. The drill would be tethered to the nuclear reactor for power throughout its drilling campaign. When it has reached the target depth of 1 km at the primary bore site, it can be transported by the Mars Towing Rover to additional areas of geological interest (e.g., along a fault line) for additional drilling. Currently, the overall launch manifest for the outpost includes 500 extra meters of drill rods. Additional drill rods (and replacement down-hole motors) would be sent to support extended drilling operations.

Platform and Driving Motors—The rig or surface platform would be similar to the conventional, Earth-based drilling platform, but on a much smaller scale. The mechanical drives and actuators needed to add and remove drill rods and store core samples are located on the rig base. The platform requires a motor to produce enough torque to turn an entire column of auger-geometry drilling rod to remove the cuttings. Some capacity for mobility, such as lightweight treads, is required to allow the rovers to tow the platform. During drilling, the platform would be anchored to the surface by wide-angle auger rods driven 1 m into the surface. The down-hole motor located within the bore, just behind the drill bit, provides the actual cutting power. Unlike terrestrial down-hole motors that can be as long as 12 meters and as heavy as 1,600 kg, the motor used for this Mars outpost has a relatively low power and mass. The down-hole motor with all the sensors weighs approximately 150 kg. An example of such a motor is shown in Figure 6.

Additional Drill Elements—Other elements of the drilling scheme include the drill bits, rods and casing.

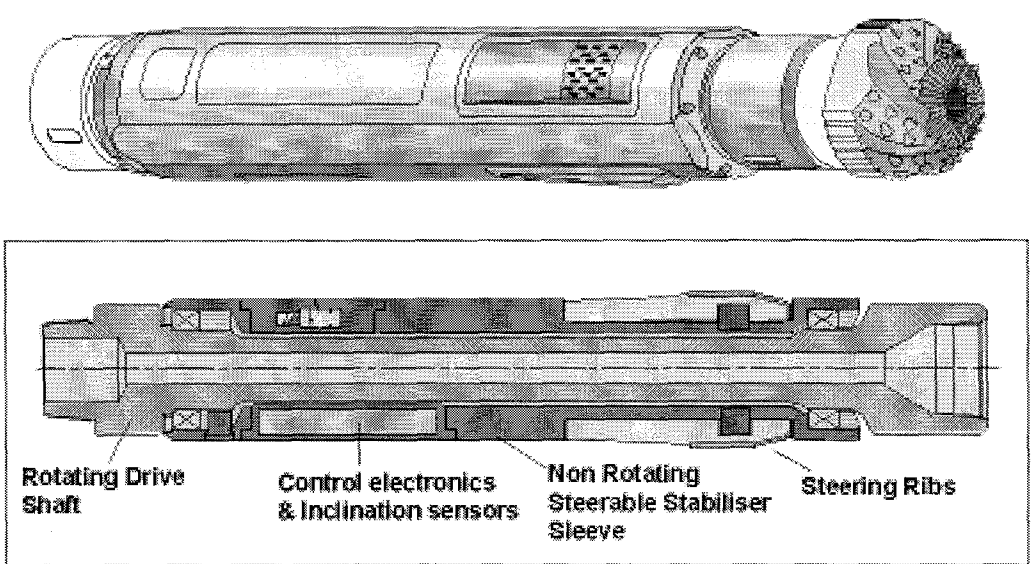

Figure 6: Down-Hole Motor [4]

Fluid-Free Drilling—Drill-bit life depends on the drilling medium, which lubricates the cutting surface as well as removing slurry, to avoid excess heating and reduce wear. Modern drilling is entirely dependent upon fluid for lubricant and cutting removal. Liquid cannot be used this way on Mars, because of its low temperature. More importantly, such a liquid system would pollute the environment. A compressed air system that poses less of a contamination threat could be used, but would disrupt the pristine conditions and lower sub-surface investigations' scientific value. Additionally, equipment to compress the low-pressure atmosphere of Mars enough to remove cuttings would be extremely massive.

Bit Selection—With no fluid used for cooling, a robust bit must be used, and the drill rate must be kept relatively slow. The drill bit for core removal would be a self-sharpening diamond (such as the Tricone corer bit by Hughes Christensen). To avoid excessive heat and allow one bit to last until the target depth of 1000 m is reached, a drilling rate of about 1 m per day was selected.

Auger Cutting Removal—When the cutting tool breaks the rock, the cuttings volume typically increases by 30 to 40%. Mechanical auger cutting removal is the only known method to remove loose cuttings from the bore-hole that does not require some type of cutting liquid or high pressure gas. Auger systems require robust, high-torque drill rods.

The composite-auger geometry drill rod advances with the motor and removes the cuttings. Embedded conductors are the pathway for power and data relay for the down-hole tools. Figure 7 shows an example of an auger-drill rod. For this concept, rod size was estimated at 5 cm for the outer diameter, 4 cm for the inner diameter. The width of the thread that spirals along the cylinder and is responsible for the cutting removal is estimated to be about 3 mm. Not including replacement rods, a total of 400 drill rods at 2.5 meters per rod will be needed to achieve the 1-km depth.

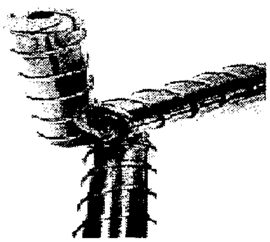

Figure 7: Auger-Drill Rod [5]

Core Retrieval—The drill system concept for this outpost calls for retrieval of core samples of about 1-cm diameter, and 1-meter length. Though there are several methods to do this in Earth-based systems, no methods have proven to work autonomously. Current industry core-retrieval devices also cannot meet planetary-protection standards.

The 1000-m drill mass would be scaled up from an existing 200-m drill concept [6]. It is estimated that the system, not including the low-mass composite drill rod, would be about 1500 kg (Figure 8). The drill rod itself can be packaged into dispenser units holding 250 meters of rods, with a mass of about 200 kg per unit. The power requirement would also be scaled up from the 200-meter drill concept. Though no firm estimates are possible, 5 kW is a reasonable power constraint for the system at the specified drilling rate.

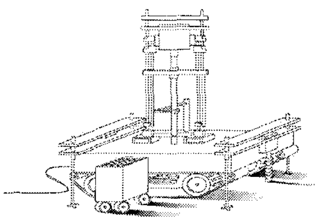

Figure 8: Deep Drill

The drill payload would launch on a Delta IV Heavy, and include the first 250 meters of drill rod and 1 km of power tether, so the drilling could begin even if the separate flight with additional drill rods and the power tether were lost.

In-Situ Sample Analysis Equipment—A total of 200 kg was allotted for the in-situ analysis equipment to be flown in 2014. Though this concept was not fully fleshed out, it is intended to be an autonomous mini-laboratory, capable of handling the meter-long core samples retrieved by the drill. It might possess a conveyance system, which would send the sample by an internal array of instruments (such as spectrometers, imagers, etc.). It would provide detailed information on the characteristics of each sample as the drilling campaign progressed.

Communication Satellite—A communication satellite would also be launched in 2014, to expand the outpost communication infrastructure. Like the communication hub, the satellite has a 5-meter High Gain Antenna to relay the HDTV data stream directly to Earth. This satellite would be in an areostationary orbit—similar to a geosynchronous satellite at Earth, but around Mars—above the outpost site.

The orbiting platform has the Earth in sight for longer periods than the hub on the surface, allowing for increased communications. This moves the communications infrastructure closer to the goal of supporting continuous live HDTV coverage. The normal operational mode would be to relay data from the outpost elements through the hub to the satellite and back to the Earth. However, the communication hub would still have the ability to relay data directly to Earth, for redundancy.

Because of geometry between the planets, continuous, "around the clock," coverage from the HDTV cameras is not possible using only the communication hub and the single-areostationary satellite. With the ground element alone, there would be several hours of blackout per day, due to the rotation of Mars. In addition, there would be several weeks of blackout due to Mars' occultation with the Sun (conjunction). Adding an areostationary satellite in Mars' orbit reduces but does not eliminate these blackout periods.

Though they were not included in this outpost design, and their development costs were not included in our estimate, two additional satellites would be needed to obtain continuous HDTV coverage. These could be placed at the Lagrange points 60 degrees off the Sun in Mars orbit. One could lead Mars, placed at L4, while the other lags the planet, in L5. Both would have the 5-m antenna mentioned above. Adding only one satellite in L4 or L5 would greatly reduce the blackout periods due to the motion of the planets. Gaps in communication would be brief and infrequent. However satellites at both points (Figure 9) are needed for truly seamless coverage.

Logistics Supplies—An additional three-quarters km of casing would be part of the payload of this logistical flight. It would be packaged in 3 dispensers, at 200 kg per unit. The 2 km (200 kg) of tether that will act as rover-charging points are also included in this flight. The in-situ analysis equipment described above completes the launch manifest, bringing the total mass to 1000 kg. The set would possibly be launched on an Atlas V Medium class vehicle.

Opportunity 2016: Enhanced Science—With the main drilling campaign underway and the communication infrastructure in place, there is an opportunity to significantly enhance the science capability of the outpost in 2016. A science rover would be sent, along with a generous collection of stand-alone science instruments. Two more logistics flights would also sent, along with additional drill stems and power tether, to support the planned drilling operations.

Science Rover—Though the original reconnaissance rover carries some science instruments, this rover has a greatly extended science capability. In addition to a larger instrument-payload capacity, the instruments themselves can be tailored to the region around the outpost site, based upon data returned by the first rover and the results of the seismic survey.

Like the outpost rovers, each science rover would carry an HDTV camera and a communication antenna. Similarly, it also relies upon rechargeable batteries for power, which are replaced by the towing rover as required. As with the long-lived, long-range rover, the science rover would be designed to travel about one month between charges, at a speed of around 2 km per sol. It would be launched as part of the payload on an Atlas V Medium class vehicle, along with the science instruments described in the following section. A conceptual drawing of the rover is shown in Figure 10.

In-Situ Science Instruments— Four science instrument modules are included in the scenario. These 4 are interchangeable payloads for the rovers, used to perform in-situ experiments at different locations around the outpost. The modules include instrumentation for the following investigations: soil analysis, mineralogy, organic detection, atmospheric chemistry, subsurface analysis, and surface processes such as metrology. Additionally, each module contains a small imager to record the area being investigated and a robotic arm to collect samples for the instruments.

Though the science rover would be the primary vehicle for the modules, they could be interchanged with the other rovers and brought to a site to perform autonomous analysis. Each module could have a mass on the order of 40 kg.

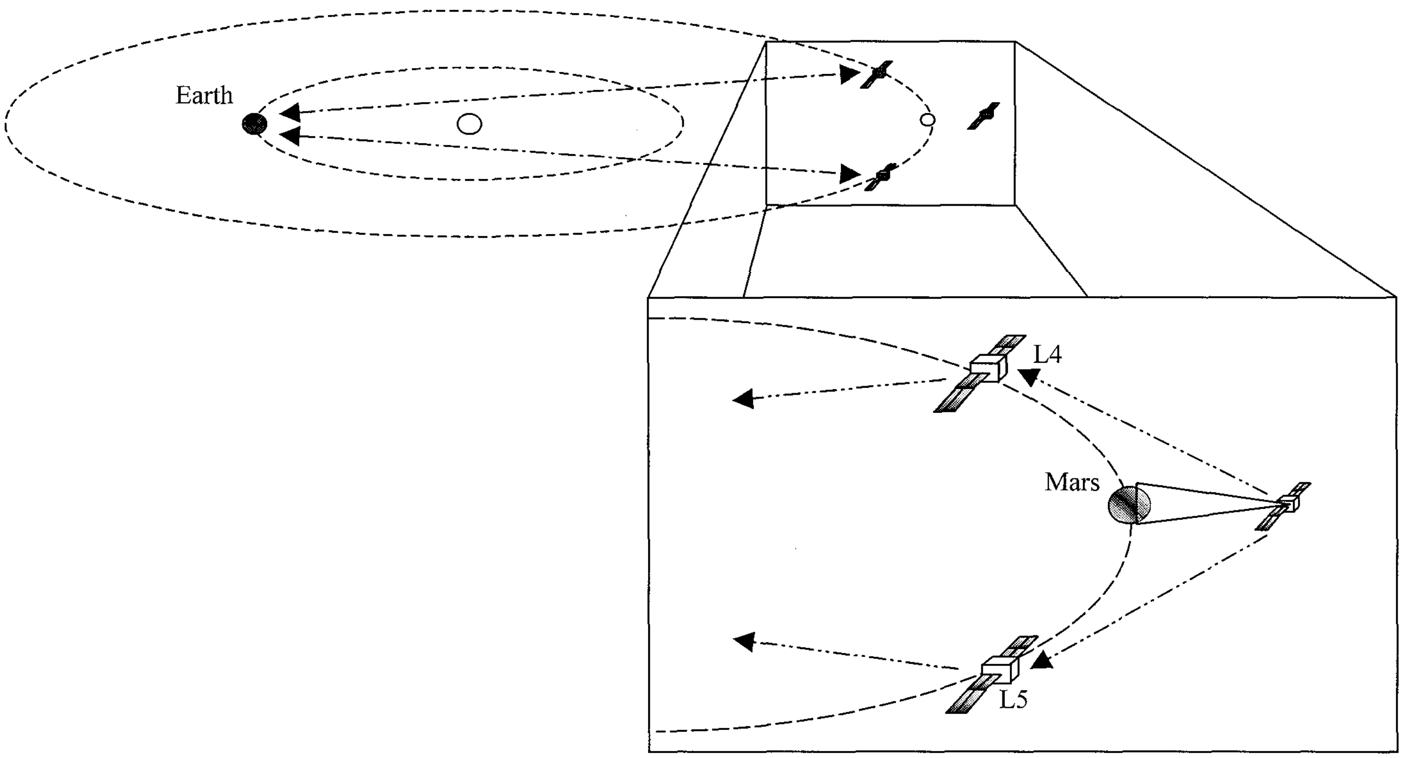

Figure 9: Relay Satellites

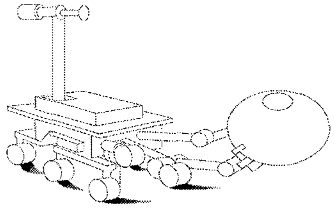

Figure 10: Science Rover

Opportunity 2018: Sample Return—At this stage the outpost would be provided with a sample return system. Because the outpost site already includes rovers, a drill and sample analysis equipment, the system consists of a Mars Ascent Vehicle (MAV) and Earth Return Vehicle (ERV). To increase the amount of sample for a given system mass, the ERV would be left in orbit around Mars and only the MAV would landed. At this point, samples retrieved by the drill have been analyzed by in-situ equipment. Those of greatest scientific interest have been stored for return, including samples from depths of up to 1 km, depending upon the success of the drilling campaign. Since such samples are of increased scientific value, the MAV should include the capacity to maintain the samples at Mars' ambient conditions. Once a cache of high-value samples is created, it would be loaded (using the robotic arms of either the towing or the science rover) into the MAV. After lift-off, it will rendezvous with the orbiting ERV, which will then return to Earth on a Solar Electric Propulsion (SEP) trajectory. This scheme provides a way to obtain deep, pre-analyzed and screened sample sets for Earth return.

The MAV could be designed to wait on the surface (even for years) until a suitable sample would be selected and a decision made to return it. Including propellant and payload, it can weigh as much as 2000 kg (the maximum payload of the proposed outpost lander), to maximize the amount of sample returned. It would be launched from Earth on a Delta IV Heavy vehicle. The orbiter can be designed to wait in orbit for a period of years as well. A sample return orbiter from a previous study is estimated to weigh around 600 kg with propellant [7]. An orbiter of this size could be launched from Earth on an Atlas V medium class launch vehicle. Figure 11 is a conceptual drawing of the MAV of the sample return system, on the outpost lander.

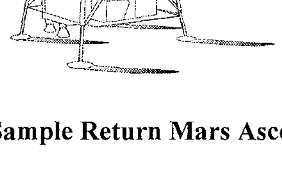

Figure 11: Sample Return Mars Ascent Vehicle

Opportunities 2020, 2022 and Beyond—The equipment listed for these outlying years are placeholders for a variety of possible activities. In 2020 and at any time of the evolution of the outpost, the site could be used to carry out human precursor demonstrations, such as habitat testing and In-Situ Resource Utilization (ISRU) experiments (e.g O_2 production).

At this stage, the outpost should also be rigorously scrutinized and assessed (i.e. a formal extended operations review should be carried out). If a decision is made to continue robotic exploration, advanced mobile units can be sent (as the previous rovers may be nearing or exceeding their design lives and rover technology may have advanced). The outpost could be expanded and/or become a springboard for outposts at other locations. When it reaches the end of it's life in this timeframe, the nuclear reactor would need to be replaced as well. If the site is deemed suitable for human exploration, human operation gear and full scale ISRU equipment can be emplaced, reactor decommissioning can be initiated, and remnant radiation from the reactor would have to be taken into consideration.

Water Contingency Scenario

Another obvious branching point occurs if significant quantities of water are discovered at any time during the drilling campaign. At that point, the H_2O contingency plan should be incorporated into the outpost scheme. If this discovery occurs prior to the 2018 opportunity, for instance, a wet sample return system launch would replace the dry sample return system mission baselined for that year. ISRU systems capable of retrieving and processing the water would later be put into place. Elements from the original outpost plan (such as human precursor demos and advanced rovers.) would continue to be added, based on the likelihood that this discovery would lead to decisions to expand/send humans to the outpost site.

3. Findings: Science Benefits of Outpost

Mars Exploration Goals and Objectives

As previously indicated, there were several drivers that molded the outpost designed in this study, including the desire to investigate the feasibility of using such technologies as a space nuclear reactor and a deep drilling system on Mars. However, determining the benefits of carrying out science investigations in an outpost setting was also a major goal. The following sections describe the overall goals and objectives of the Mars exploration program, and the approach taken to measure the merits of this outpost design relative to those objectives.

Science Goals and Objectives—There are four broad goals associated with the Mars exploration program. Currently those are to determine if life ever arose, determine the climate, determine the geology, and prepare for human exploration [8]. The science community has been working to separate those goals into more specific objectives, then break the objectives into required investigations, and determine the precise measurements needed for each.

Mars Objectives and Investigations List—A list of 10 objectives and 51 associated investigations was compiled by the Mars Exploration Payload Analysis Group (MEPAG) and the Mars Ad hoc Science Team (MAST). As an example, one objective derived from one of the main goals is "Determine if life existed in the past". A specific investigation under that objective would be to search for fossils in sedimentary rocks.

Investigation Requirements—The first step in relating the outpost to these identified objectives and investigations was to characterize the site requirements of the investigations themselves. Investigations were noted as being achievable by using measurements taken at a single site versus requiring measurements from multiple, widespread sites on the surface. Those requiring aerial or orbital measurements were also noted. Because this outpost concept focuses on subsurface characterization using elements on the Martian surface, it does not directly support investigations requiring aerial and orbital measurements (although other outpost concepts could serve as aerial investigation centers).

Outpost Capabilities—The capabilities of this particular outpost were listed, including long-term presence, multiple missions (logistical support), surface mobility, subsurface access, high power availability and sample return capability. The long-term presence applies directly to those investigations requiring long-term, continuous data sets (such as measuring the climate in a region for an entire Martian year). Along with surface mobility, it also benefits those investigations intended to search for specific phenomenon and map regions with high resolution from the surface – allowing more time for those activities increases their chance for success. The investigations associated with the geological goal were most impacted by access to the subsurface. High power was deemed necessary mainly for deep drilling activities, but also for contingency activities such as major construction demos or In-Situ Resource Utilization (ISRU).

Outpost Impact—A matrix was built to show the correspondence between each investigation and the outpost capabilities that could be useful in carrying it out. Those investigations that required deep drilling and thus long-term presence and high power can be said to be "enabled" by this outpost concept. This term also applies to those investigations that were inherently achieved by this outpost (such as demonstrating deep drilling, and putting a high capacity power system into place). These comprised about 30 percent of the total investigations. Those that required a long-term surface presence, as well as surface mobility or sample return capability can be said to be "facilitated" by the outpost concept. These included a additional 30 percent of the total investigations. Thus more than half of the investigations identified are enhanced or enabled by this particular outpost design.

4. Findings: Technology Needs

General Technology Needs

Launch Vehicles and Entry, Decent and Landing (EDL)—Among the most obvious technology needs that were noted during this study were those concerning launch vehicle and EDL capabilities. The primary driver for this was the need to transport very massive elements (in this case, the reactor, deep drill system and MAV) to the Martian surface. The availability of the Delta IV Heavy vehicle mitigates the mass limitations, but does not provide the entire solution. An outpost lander was conceived, to support transport of heavy elements to the Martian surface.

Launch Vehicle Constraint—Because of the short duration of each launch opportunity (20-40 days), launch range constraints become a serious problem for mounting a multi-element mission to Mars. While launches to Mars from the Western Test Range at Vandenberg AFB are practical for certain trajectories and launch opportunities, the architecture was selected to be independent of launch opportunity so Vandenberg launches were not included. This leaves only Cape Canaveral as a viable option for large US launch vehicles. One thing not considered, but which could help alleviate this limitation, is using the Ariane V launcher and its French Guyana launch site. Realistically, it may be impossible to have more than two launches of a particular launch vehicle from a single site. Also, since the overall launch range throughput would be limited, the total number of launches per launch opportunity would be limited as well. The exact number would be difficult to determine, but is probably no more than four to six. Because of the large mass of several elements such as the reactor and drill, Delta IV Heavy launch vehicles have been used extensively in this scenario. However, assuming two Delta IV Heavy launches in a single 20-40 day period may be unrealistic, due to the historically long on-pad times of heavy-lift vehicles and the limited number of launch pads and processing bays. This could provide the incentive to construct additional pads and bays, which might also be needed for future human exploration missions.

EDL Requirements—With payloads of this size, traditional braking techniques such as parachutes become less practical. An Outpost Lander was conceived for this study which incorporates a mid L/D lifting-body shape into the aeroshell design. The lifting provided by the body shape reduces the size of the parachute as well as the thrust requirements for the retro rockets, thus allowing more space and mass for the payload.

Furthermore, with linked missions precision landing becomes increasingly more important. The slower speeds and greater maneuverability achievable with the mid L/D aeroshell can also improve landing precision. This scenario includes a rover dedicated to moving large elements, and could tolerate landing errors on the order of a few 10s of kilometers after the reactor power source would be in place. For other outpost scenarios that may not include such a capability, the need for outpost element interaction could greatly reduce this tolerance.

For the lander concept was developed for this scenario, a mass of 6100 kg (including landed payload) was assumed, which is roughly the capacity of a Delta IV Heavy launch vehicle for a type II trajectory with a C_3 of 18 [9]. Using mass ratios for subsystems on landers from previous JPL Team X studies, this overall outpost lander mass was estimated to include about 2000 kg for the payload [10].

Energy Storage and Power Transmission—To accomplish objectives prior to the arrival of the reactor unit, batteries and solar arrays were used for certain elements. For the purpose of this study, rechargeable lithium-ion batteries were selected for baseline energy storage for the rovers. Solar arrays were selected for the communications hub. Once the reactor arrived, power was transmitted from the reactor to the drill and communication hub via power tethers up to 20 km in length. These are feasible strategies, but they have disadvantages. For instance, battery life would be limited, requiring replacements roughly every 1,000 cycles. Batteries are also limited in terms of power output and depth of discharge. With tethers, there can be significant line losses and difficulty with heat dissipation when transmitting high power over great distances. Additionally, there are difficulties associated with deploying and moving such very long tethers. Damage can also occur at tether connection points, where connectors can fail after repeated use.

Another option for energy storage would be regenerative fuel cells. A fixed amount of water could be taken to the outpost, where power from the reactor could be used to electrolyze it into hydrogen and oxygen. Stationary storage tanks could serve as fuel stations for the rovers, and smaller tanks could be transported to stationary elements such as the drill and communication hub. The "waste" water from the fuel cells would be returned to the reactor for electrolysis, creating a continuous and (theoretically) closed loop process. Issues associated with such a scheme are the low maturity level of regenerative fuel cells and the difficulties associated with containing leaks when storing gaseous hydrogen. In practice, escaping gas could necessitate a periodic replenishment of the water supply.

Finally, the development of advanced, long-term dust mitigation techniques would be necessary if solar arrays are used to power the communications hub.

Element Specific Technology Needs

Space Nuclear Reactor—Nuclear power generation is a mature technology; reactors have been used to produce power on Earth for decades. This form of power generation could also be a major enabling technology for future space exploration. However, further technology development would be necessary before such reactors can be used in extra-terrestrial applications.

Further study and development concerning radiation shielding issues would be required. Earth-based systems can incorporate massive shields to obtain any level of radiation protection desired. However, this approach is not feasible for space hardware, because of the mass constraints associated with space travel. For this study, minimal shielding was used, adequate for protecting the instrumentation within a specified zone. However, greater levels of shielding may be desired, for human exploration or planetary protection issues. Conventional man-rated shielding could increase the mass of the reactor used in this outpost design by a factor of two, although in-situ shielding options could also be explored.

The design of space reactor systems must also be made robust enough to withstand the loading and vibration of the launch environment. In depth safety investigations would also need to be made, concerning the launch and use of the device.

The current life-expectancy estimate for this reactor concept is five to seven years at full power, associated with the possibility of failure in the power-conversion units and reactor-control mechanisms. This is a great increase over that achievable with current photo-voltaic and battery-power sources, at high power levels. But, because the power source is such a critical outpost component, further technology development to increase this lifetime would still be beneficial.

Rovers—As mentioned before, there is a need to develop replaceable, rechargeable batteries capable of providing adequate power for the all the rovers. With its heavy towing tasks, this is especially important for the MTR.

Autonomy is another area that requires significant development, for all of the mobile elements. This includes autonomous navigation, hazard avoidance, fault diagnostics and deployment. For example, it would be desirable for a rover to be able to detect a low battery charge, determine its position with respect to the charging station and proceed there to be charged without human intervention. Also, seismic sensor-array deployment is a complex but repetitive towing-rover task, which could be automated.

There are many issues associated with the towing rover that merit further study. This concept included advanced batteries and a heavy, tracked design. To transport very massive loads, it may be necessary to incorporate other measures such as chemical propulsion assistance, connecting directly to the reactor while towing, using grappling hooks, or exploring other new technology developments.

Deep Drill System—Like nuclear power generation, deep drilling is another application that is extremely mature. Similarly, terrestrial rigs that reach depths of 1 km or more tend to be very massive. They typically are of rigid steel construction, incorporate an hydraulic press and steel-drill rods to provide adequate down-hole forces for high-drill rates and use a liquid coolant and cutting removal system.

Light-weight, high-strength materials are needed to enable the design of a deep drilling system that fits within the mass constraints associated with space flight. Automation is another major area requiring technology development, for the deep drilling application. Automated drill rod handling and core retrieval exist today. However, these technologies are dependent on human oversight - no fully autonomous drill has ever reached a depth greater than 20 meters without requiring a human to correct for errors.

Communication Infrastructure—One of the concerns of telecommunications is developing a 5-m antenna for the communication hub and satellites. These will require inflatable antenna technology, which is currently at a low level of maturity. Additionally, there is a concern with the Earth-based end of the communication loop. To handle the demanding data rates associated with this multi-mission scheme, DSN would have to be upgraded or expanded beyond its present capability. Another area for development involves determining the trajectories and techniques needed to deliver satellites to the Lagrange relay points.

Sample return strategy and implementation—There are many well-known issues associated with returning samples to Earth. The outpost setting simplifies the problem, since the equipment for gathering high quality samples (the rovers, drill and sample analysis equipment) are already in place before the "sample return" phase begins. However, several difficult issues remain to be solved, including that of autonomous rendezvous and docking (for the MAV and orbiting ERV), and sample containment and environmental protection issues once the sample reaches Earth. A successful, non-outpost sample return mission may have been undertaken by the 2018 date given in this conceptual scenario. Outpost mission designers could then take advantage of that heritage to enhance the performance and science return of this outpost-supported sample return flight.

Cost— As previously mentioned, the design was not tailored to fit within the current NASA budget. Including development costs for the major elements, such an aggressive, far-reaching plan might be implemented at a cost on the order of one billion dollars per year.

5. Findings: Logistics

General

The proposed outpost scenario with its multiple launches and interdependent landed elements represents a significant change from previous Mars missions which utilize a single launch vehicle and independent spacecraft.

Lessons Learned—As the outpost architecture was developed, several logistics lessons became apparent. First, the limitation of two heavy-vehicle launches per launch opportunity severely limits the launch manifest. This is especially true when the drill and reactor are launched. To even out the launch manifest, this limit caused the towing rover to be shifted to an earlier launch opportunity. A second lesson was that the drill stems and especially the power tether represent a large mass, which caused the planned tether and drill-stem lengths to be shortened. A third lesson was that the reactor's lifetime is critical to the mission's success and duration. Thus, it would be helpful to either fly a spare reactor unit, or make some systems reactor-independent—like the seismic-survey equipment became when an explosive-based system rather than a multi-kW acoustic "thumper" was chosen to power it.

Reliability—The described architecture was a single-string design and as a result has a low system reliability due to the large number of launches and landed elements required for the subsurface mapping and sample return objectives. Realistically, either major elements must be made modular with the possibility of replacement of failed systems or entire spare elements must be used to ensure a high probability of overall mission success. A combined approach utilizing a spare towing rover (with a robotic arm) and a reactor with replaceable modules and/or redundant subsystems might be one solution.

At such a conceptual level, subsystem reliabilities represent design goals rather than design results. However by making reasonable assumptions about subsystem reliabilities, the effects of the interdependency between elements on the overall mission reliability can be identified. This is important since once such interdependency is understood, a repair or replacement strategy can be formulated to maximize chance of success for minimum cost. Due to budget and schedule constraints, a repair or replacement strategy has not yet been formulated or analyzed.

Generalized Availability Program (GAP) Analysis

As the study progressed, it was realized that a structured method of modeling the outpost reliability was needed. The Aerospace Corporation offered GAP Analysis as a tool that might be applied to such a complex scenario. The following section describes the program.

Overview—The Generalized Availability Program (GAP) is a software program developed by The Aerospace Corporation to assist the USAF Space Command in its planning of future space systems. GAP performs Monte

Carlo simulations using launch vehicle and space vehicle reliabilities to estimate the probability of having a functioning system at some future point in time or over a period of time. GAP has been successfully used for planning of many satellite constellations for the USAF including the Global Positioning System (GPS). This study is the first use of GAP for interplanetary exploration.

Process—To estimate the landed element reliabilities needed as GAP inputs, fault trees were constructed identifying major types of failure modes. Failures were classified by the system where the fault occurred (power, sensors, mobility, etc.), not the cause of the fault itself (i.e., manufacturing defect, assembly error, human operator error, etc.). An overall 95% reliability was assumed for cruise stage, entry, descent, and landing operations for each element. Launch vehicle reliabilities used historical data for the Delta II, and the program requirement for the yet-to-fly Delta IV and Atlas V. Subsystem reliabilities values at the end of the expected design life were assumed for each element.

Despite the fact that the assumed subsystem reliabilities were high (usually 97% or better), the overall mission reliability was low. This is due to the large number of elements (without any spares) required to accomplish the mission objectives in the current architecture. Figure 12 presents a sample fault tree for the towing rover, showing a 22% failure rate after 10 years.

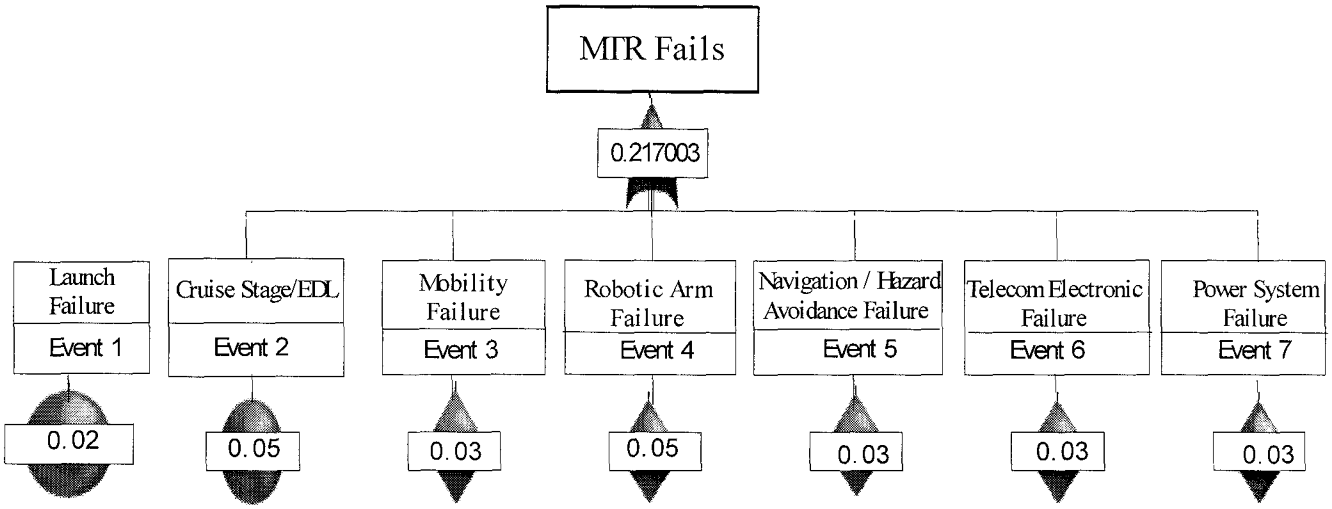

Figure 12: Sample Fault Tree for the Towing Rover

Other Inputs—Another important GAP input is its elements' expected design lifetimes. They exceed the required mission objectives' operational period, so a linear-failure distribution was assumed. If long-term goals are addressed, more sophisticated failure distributions would be needed.

Once element reliabilities and failure distributions had been established, estimates were made using GAP for the combined availability of the system at future points in time. Availability in this context was defined as continued full operational capability. For a given objective, for example obtaining a 0.25 km deep sample, different elements had to deploy successfully and operate for differing amounts of time. For obtaining a 0.25 km deep core sample, the towing rover, drill and reactor had to successfully survive for thirty-six, six, and six months, respectively. Future use of the GAP tool can allow the effect of selected component or element redundancy, longer element life, changes in element, launch vehicle or EDL reliability, different launch vehicle selection, or different number and order of launches on mission risk to be examined. If used in this way, GAP can help identify an optimal Mars Outpost architecture that balances risk, cost and performance of mission goals.

6. CONCLUSIONS

This study has taken the first steps towards building an understanding of the issues involved in developing and maintaining multi-element, long-term, robotic outposts on Mars. The process of designing and exploring this particular conceptual scenario has shed light upon the scientific usefulness, technology needs and logistical challenges that can be associated with such a multi-mission plan.

It has been seen that a substantial number of investigations desired by the scientific community are well suited to this type of outpost setting. Several technology issues were highlighted, including the need for a mid-L/D heavy lander, the possible need for additional heavy launch vehicle processing facilities and the need for developing autonomous operation capabilities for the deep drilling system. An approach was investigated for determining the reliability of long-term, conceptual multi-mission schemes. Use of fault-tree analysis and The Aerospace Corporation-developed General Availability Program should be investigated further. This study did not advance to the point at which the results were used to determine redundancy and sparing strategies and iterate on the outpost design.

ACKNOWLEDGEMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The Mars Long Range Planning team would like to extend thanks to those at The Aerospace Corporation, NASA Glenn, the DOE, Baker Hughes and Applied Research Associates, as well as members of Team X and other associates at JPL, for their contributions to this study. Thanks also to Thomas J. Wilson for editing and illustrating the paper.

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